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WOOD AND OTHER RENEWABLE RESOURCES

Life cycle assessment of medium density particleboard (MDP) produced in Brazil

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Abstract

Purpose The wood panel industry is one of the most important forest-based industries in Brazil. The medium density particleboard (MDP) is currently produced and consumed worldwide and represents about 50 % of the wood panel industry in Brazil. Unlike other regions, Brazilian MDP is produced from dedicated eucalyptus plantations and heavy fuel oil is an important energy source in MDP manufacture, which may result in a different environmental profile. This paper presents a life cycle assessment of MDP panel produced in Brazil and suggests improvement opportunities by assessing alternative production scenarios.

Methods The cradle-to-gate assessment of 1 m^3 of MDP produced in Brazil considered two main subsystems: forest and industrial production. Detailed inventories for Brazilian eucalyptus production and MDP industrial production were collected as a result of technical visits to Brazilian MDP producers (foreground systems) as well as literature review (mainly background systems). The potential environmental impacts of MDP were assessed in terms of seven impact categories using CML (abiotic depletion, acidification, global warming, eutrophication, and photochemical oxidation) and USEtox (ecotoxicity and human toxicity) impact assessment methods in order to identify the main hotspots.

Results and discussion The industrial production was responsible for most of the impacts in all impact categories, except ecotoxicity (EC). The main hotspots identified were the use of heavy fuel oil (HFO) as a thermal energy source in MDP manufacture and the production of urea–formaldehyde (UF) resin used as synthetic adhesive. Glyphosate herbicide application in soil in forestry operations was the main responsible for the impacts in EC. Scenarios for HFO substitution were assessed and results showed that substituting HFO for in-mill wood residues or diesel leads to reduced environmental impacts.

Conclusions The identification of the main hotspots in the MDP life cycle can assist the wood panel industry to improve their environmental profile. Further research should focus on UF resin production in order to reduce its environmental impacts as well as the possibility of using alternatives resins. Other sources of wood for MDP production could also be investigated (e.g., pine wood and wood residues) to assess potential improvements.

Keywords Environmental hotspots · Environmental management · Heavy fuel oil · Improvement opportunities · Medium density particleboard · Wood-based panels

1 Introduction

Brazilian planted forest areas are the eighth largest in the world and are composed of around 75 % eucalyptus and 25 % pine (ABRAF 2012). More than 90 % of this area provides raw materials to the cellulose and paper and the wood panel industries and is an important energy source for the steel industry. In

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particular, wood panel production in Brazil is the sixth largest worldwide (Biazus et al. 2010). Wood panels are composed materials produced using processed wood and a synthetic binder, whose properties can be engineered (Thoemen et al. 2010). The most common wood panels are: particleboards (or medium density particleboard (MDP)); oriented strand boards (OSB); fiberboards, particularly high-density and medium-density fiberboards; and veneer-based products including plywood and laminated veneer lumber. Wood panels are mainly used in the furniture and construction sectors. In Brazil, about 50 % of the wood panel production is MDP. Brazilian MDP is an engineered panel made of wooden particles from planted forest, mainly *Eucalyptus*. It is mostly used in the production of furniture, such as tabletops, cupboard sides, shelves and dividers, and secondarily, in buildings, for instance wood floors (Biazus et al. 2010).

There is an increasing pressure on companies to reduce the environmental impacts of the products. In order to improve the environmental performance of products, it is important to take a life cycle approach (Remmen 2007). The life cycle assessment (LCA) methodology can be used to identify the most relevant environmental impacts and the main hotspots, i.e., the processes that contribute the most to the environmental impacts (Baumann and Tillmann 2004). To the best of our knowledge, there are no published LCAs of MDP produced in Brazil, although a number of studies have been developed for other regions (e.g., Spain (Rivela et al. 2006), USA (Wilson 2010), and Portugal (Garcia and Freire 2012)). The main differences regarding MDP production in Brazil and in the identified regions are related to the sources of biomass and the on-site energy generation technologies and fuels used. While in the USA and Europe, wood used to produce MDP is mostly waste wood (preconsumer, e.g., from forest operations and sawmills, and postconsumer); in Brazil, dedicated forests provide biomass to MDP industries. On the other hand, recent studies have been analyzed the addition of waste to produce wood panels in Brazil (Barros Filho et al. 2011; Silva et al. 2012). Regarding fuel use as a thermal energy source in the MDP manufacturing process, both US and European studies report the use of natural gas and wood residues; while in Brazilian mills, both heavy fuel oil (HFO) and wood residues are used. On-site cogeneration is also used in European mills and not in Brazilian mills. In view of the above, this paper presents LCA of MDP panel produced in Brazil and suggests improvement opportunities by assessing alternative production scenarios.

2 Life cycle model and inventory

2.1 System boundary

An MDP panel is composed of a synthetic adhesive matrix and a reinforcing phase composed of wood particles, which are combined by the application of heat and pressure to the consolidation of the panel. The wood particles are arranged in three layers. The synthetic adhesive is composed of a thermoset resin, usually urea–formaldehyde (UF), which is the binding agent; paraffin emulsion, which improves the hygroscopic properties of the panel; and a catalyst (ammonium chloride/sulfate), whose function is to accelerate the cure of the resin during the pressing cycle. Figure 1 presents the system boundary of the MDP life cycle from a cradle-to-gate perspective. The functional unit is the production of 1 m^3 of uncoated MDP, with nominal thickness of 15 mm, average density of 630 kg/m^3, and 8 % moisture content. The forest and industrial production subsystems as well as the ancillary subsystems are explained in detail in the next paragraphs.

MDP panel production is characterized by the use of wood coming from dedicated eucalyptus crops. The average productivity of eucalyptus was assumed at 45 m^3/ha year (290 m^3/ha after 6.5 years of growth). The main activities included in forest production are: cultivation of seedlings, soil preparation, seedling planting, forest management, harvesting, and transport of wood. The first step is the production of seedlings by piling. After 3 months, the seedlings are transported to the field for planting. Before planting, the soil is prepared through the building of road infrastructures and crop treatment operations, such as soil fertilizing with nitrogen (N)-, phosphorus (P)-, and potassium (K)-based fertilizers; limestone application; and treatment with pesticides. After planting, forest management operations, such as thinning and pruning of trees, are performed for the following 6.5 years until the cutting age of the trees is reached. Wood is then harvested and transported to the manufacturing site using semitrailer trucks. Since there has not been a significant increase in eucalyptus planted areas dedicated to the production of wood to the MDP industry in Brazil in the last 20 years, no land use change was assumed to have occurred (IBGE 2007). Therefore, carbon changes due to land use change were not assessed.

The main activities included in the industrial production are: reception and storage of wood logs; production, drying, and classification of particles; blending; mat forming, and pressing; and finishing. Stored wood logs are debarked and chips and flakes are produced using choppers and ring flakers. The wood particles are then dried and classified. The larger particles form the internal layer of the panel, while the smaller ones are incorporated in the external layers. Bark and other wood residues from the manufacturing process as well as HFO are burned to produce hot gas for particle drying and hot pressing processes. The dried particles are then blended with the synthetic adhesive and a mat of glued particles is made using feeding machines which form the three layers of the panel. The next steps are the prepressing and hot pressing (160–200 °C) of the mat to consolidate the panel. Afterwards, the panel is cut to the final dimensions and sanded.

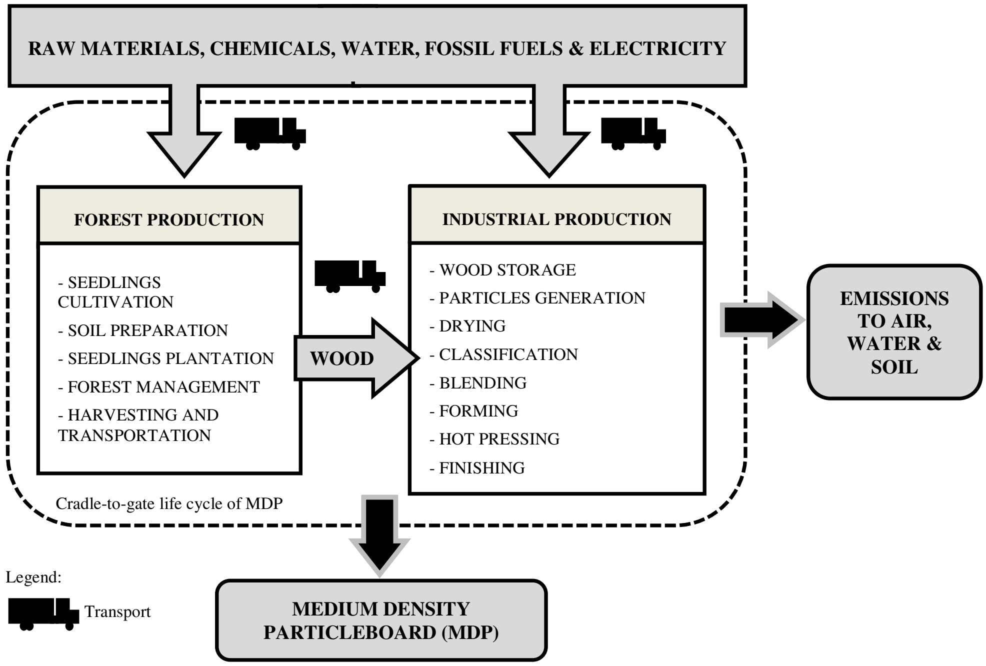

Fig. 1 System boundary of the MDP life-cycle model (cradle-to-gate perspective)

A number of ancillary subsystems were included within the system boundary. These include energy inputs such as electricity generation (Brazilian mix) and fuels (diesel and HFO); the production of chemicals, such as limestone, fertilizers, and herbicides for the forest production subsystem and UF resin; paraffin emulsion and ammonium sulfate for the industrial production subsystem; and transportation processes.

Table 1 Forestry production inventory (1 m^3 of MDP)

Inputs		Outputs	
Limestone (as calcium carbonate)	20 kg	Wood (as logs)	687.2 kg
Lubricants (oil and grease)	0.79 g		
Seedlings	0.52 kg		
Water	85 kg		
Energy consumption		Emissions to air	
Diesel	4.85 kg	Ammonia	75.1 g
Electricity	0.18 MJ	Carbon dioxide	15.1 kg
		Carbon monoxide	53.8 g
		Glyphosate particles	0.27 kg
		Nitrogen dioxide	10 g
		Nitrogen oxides	0.116 kg
		Particulate matter	10.3 g
		Sulfur dioxide	8.07 g
		VOCNM	78 g
Pesticides		Emissions to water	
Sulfluramid formicide	0.112 kg	Glyphosate particles	1.44 g
Glyphosate herbicide	0.154 kg	Runoff surface (from P_2O_5)	0.11 kg
		Runoff surface and percolation (from N)	0.1 kg
Fertilizers		Emissions to soil	
Potassium chloride (60 % K_2O)	2.75 kg	Lubricants residue	2.36 g
Urea (46 % N)	0.1 kg		
Ammonium sulfate (21.2 % N)	0.4 kg		
Superphosphate (18.5 % P_2O_5)	5.77 kg		

VOCNM volatile organic compounds nonmethane

2.2 Data quality and assumptions

Inventory data for the foreground system (forest and industrial production) consisted of average data obtained from MDP panel manufacturing companies in Brazil. Data for three companies, located in the States of São Paulo and Minas Gerais, representing 57 % of the Brazilian MDP panel production (1,733,785 m^3 in 2011), was collected covering both forest and industrial production stages. Average values representing 1 year of MDP production were obtained from on-site measurements and internal company documents such as records of raw material consumption, emissions, and waste management inventories, during 2011 and 2012. Data for the production of UF resin was collected from a chemical plant located in Minas Gerais.

When process emission data was not available, these were estimated based on the literature, as described next. Regarding forest operation, emissions from the application of glyphosate herbicide in soil were calculated using PestLCI 1.1.15 software (Birkved and Hauschild 2006). Emissions to air and water resulting from the application of fertilizers were calculated based on OSB/WSTB (2000) for urea and ammonium sulfate, and Shigaki (2006) for superphosphate. Concerning the industrial production, emissions from HFO were calculated using IPCC emission factors (IPCC 2006) while waste wood combustion emissions were based on the US Life Cycle Inventory (USLCI) database (NREL 2009a). Free formaldehyde and volatile organic compounds (VOC) emissions were taken from Chipanski (2006) and Wilson (2010), respectively.

Table 1 shows the inventory of forest production and Table 2 the inventory for the industrial production of 1 m^3 of MDP. In Table 1, the functional unit is equivalent to 0.005 ha (50 m^2) of cultivated area.

Inventory data for the remaining ancillary inputs (background system) was collected from the literature. The production of ammonium sulfate and urea in Brazil was obtained from Ribeiro (2009). Data for the Brazilian production of limestone and superphospfate was collected in Ometto (2005) and Monteiro (2008), respectively. The

Table 2 Industrial production inventory (1 m^3 of MDP)

Inputs		Outputs	
Ammonium sulfate	1.38 kg	MDP panel	630 kg
Lubricants (oil and grease)	18 g		
Paraffin emulsion[a]	5.47 kg		
UF resin[b]	71.7 kg		
Water	90.4 kg		
Wood (as logs)[c]	687.2 kg		
Energy consumption		Emissions to air	
Diesel	1.72 kg	Ash (from wood residue)	0.39 kg
Electricity	507 MJ	Carbon dioxide (from fossil fuel)[d]	48 kg
Heavy fuel oil	13.7 kg	Carbon monoxide	0.19 kg
Wood residues	38.5 kg	VOC (not specified)	0.36 kg
		Formaldehyde	0.15 kg
		Hydrocarbons (not specified)	1.64 g
		Methane	1.69 g
		Nitrogen oxides	0.18 kg
		Particulate matter (not specified)	0.18 kg
		Sulfur oxides	1.32 kg
		VOCNM	9.48E-04 g
		Emissions to water	
		Ammonia	0.121 g
		BOD	0.616 g
		Effluent (not specified)	6 kg
		Formaldehyde	7.29E-02 g
		Suspended solids	24.4 g
		Emissions to soil	
		Lubricant residues	15.9 g
		Wood residues	97.2 kg

VOC volatile organic compounds, *BOD* biochemical oxygen demand

[a]Paraffin emulsion: weight at 100 % solids (solid content of 60 %)

[b]UF resin: weight at 100 % solids (solid content of 67 %); molar ratio formaldehyde/urea of 1.38

[c]Wood (as logs): average density of 474 kg/m^3 (oven dry) or 1.45 m^3/m^3 of MDP

[d]Biogenic carbon dioxide emission to air was 33.8 kg/m^3 of MDP—not included in inventory

Table 3 Transport distances

Subsystem	Description	Distance (km)
Forestry	Ammonium sulfate (fertilizer, 21.2 % N)	1,900
Forestry	Glyphosate herbicide	1,915
Forestry	Limestone (as calcium carbonate)	470
Forestry	Potassium chloride (fertilizer, 60 % K_2O)	2,153
Forestry	Superphosphate (fertilizer,18.5 % P_2O_5)	1,930
Forestry	Urea (fertilizer, 46 % N)	2,025
Industrial	Ammonium sulfate (as catalyst)	1,900
Industrial	Paraffin emulsion	2,600
Forestry/industrial	Diesel	122
Industrial	Heavy fuel oil	122
Industrial	Urea formaldehyde resin	500
Industrial	Wood	80

Brazilian Life-Cycle Inventory Systems (SICV Brasil 2009) was the data source for diesel production in Brazil. Data for the production of glyphosate was obtained from the Ecoinvent database (Nemecek and Kägi 2007). The USLCI database was used for data on paraffin emulsion production (NREL 2009b). Inventory data for the production of electricity generation, HFO, and transport of raw materials (PE International 2009a), and potassium chloride and operation of forest machinery (PE International 2009b) was taken from GaBi database. Average transport distances were assumed and are presented in Table 3, considering São Paulo city as the reference destination. Transport of inputs is done by EURO 3 trucks with a payload up to 27 t. Background data for raw material (urea and methanol) applied to the UF resin production was extracted from Camargo (2007) and Ribeiro (2009) studies for Brazilian contexts, respectively.

Capital goods, such as industrial machinery and infrastructure, as well as personnel activities, for instance transport of workers to and from the workplace, were not included within the system boundary. Other LCA studies of wood panels have shown that the environmental impacts of the production of capital goods are not important when compared to their operation (Rivela et al. 2006, 2007).

Table 4 Potential environmental impacts of 1 m^3 of MDP

Impact category	LCIA method	Unit	Value
Abiotic depletion (AD)	CML	kg Sb_{eq}	0.98
Acidification (AC)	CML	kg SO_{2eq}	2.40
Eutrophication (EP)	CML	kg $PO^{-3}{}_{4eq}$	0.132
Global warming (GW)	CML	kg $CO2_{eq}$	333.28
Photochemical oxidation (PO)	CML	kg C_2H_{2eq}	0.28
Ecotoxicity (EC)	USEtox	PAF m^3 day	82.80
Human toxicity (HT)	USEtox	Cases	6.71E-07

3 Life cycle impact assessment

The assessment of the environmental impacts associated with the production of MDP was performed using two life cycle impact assessment (LCIA) methods: CML 2001(Guinée et al. 2001) and USEtox 2008 (Hauschild et al. 2008; Rosenbaum et al. 2008). Five impact categories were selected from CML 2001 LCIA method and two from USEtox 2008. Table 4 shows the results of the LCIA of 1 m^3 of MDP and Fig. 2 the relative contribution of the forest and industrial production subsystems to the impacts in each impact category. As can be seen, the majority of the impacts are attributed to the industrial production subsystem, which represents more than 60 % of the impacts in each category. The exception is the ecotoxicity category, where forest production represents the highest contribution to the impacts (around 99 %). A detailed discussion of the impacts in each category is presented in the following sections.

3.1 Abiotic depletion

The industrial production subsystem was responsible for most of the impacts in abiotic depletion (AD; 83 %), mainly due to HFO (35 %) and UF resin (30 %). The AD impacts of HFO production are related to the extraction of crude oil, mineral coal, and other nonrenewable resources used in its production. Regarding UF resin, AD impacts are caused by the production of methanol and urea used to produce the resin, since they use natural gas and mineral coal in their production processes.

3.2 Acidification

The industrial production had the largest contribution to acidification (AC): 86 %. About 59 % of the impacts are due to the MDP manufacture process and are caused by the combustion of HFO, which is composed of about 5 % of sulfur. About

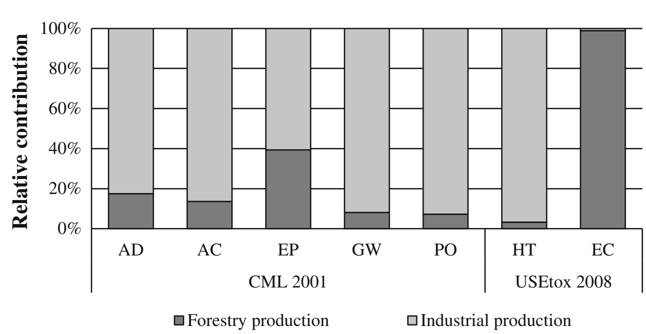

Fig. 2 Relative contribution (percent) of forestry and industrial production subsystems to each impact category

Table 5 Environmental hotspots of the MDP cradle-to-gate life-cycle

Impact category	Hotspots	Subsystem
Abiotic depletion (AD)	Heavy fuel oil/UF resin	Industrial
Acidification (AC)	Heavy fuel oil/UF resin	Industrial
Ecotoxicity (EC)	Glyphosate herbicide	Forestry
Eutrophication (EP)	Diesel/fertilizers/ UF resin	Forestry/industrial
Global warming (GW)	Electricity/heavy fuel oil/UF resin	Industrial
Human toxicity (HT)	UF resin	Industrial
Photochemical oxidation (PO)	UF resin	Industrial

11 % of the total AC impacts result from the UF resin production, due to the production of methanol and urea.

3.3 Eutrophication

Also for eutrophication (EP), the industrial production had the largest contribution (61 %). The UF resin production contributed with 33 %, due to the emission of NO_x to air and hydrocarbons to water that occur in the production of methanol and urea. The emission of NO_x from the combustion of HFO and wood residues in the industrial plant contributed to 14 % of the impacts. About 39 % of the impacts are attributed to forest production activities, namely the application of N-based fertilizers in the soil (22 %) and the use of diesel in harvesting, processing, and transport of wood (10 %).

3.4 Global warming

The industrial production shows the largest contribution to global warming (GW; 92 %). The generation of electricity was responsible for 34 % of the total GW impacts, mainly due to the use of nonrenewable sources such as coal and oil in the Brazilian mix. About 27 % of the impacts are caused by the combustion of HFO in the MDP manufacturing process. The UF resin production was responsible for about 25 % of impacts, due to methanol and urea production. The biogenic CO_2 emissions from wood combustion in the boiler were considered to be neutral as they equal the CO_2 uptaken by photosynthesis during tree growth. It should be noted that about 347 kg C is estimated to be stored in 1 m^3 of MDP (equivalent to 1,272 kg of CO_2 uptaken by photosynthesis), resulting in a net GW impact of −939 kg of CO_2 eq/m^3 of MDP.

3.5 Photochemical oxidation

The majority of impacts in the photochemical oxidation (PO) impact category are due to the industrial production (93 %). The manufacturing of MDP was responsible for about 66 % of the total impacts, as a result of VOC emissions during wood particle drying and hot pressing. About 17 % of impacts are related to the emission of CH_4, CO, NO_x, and VOCs in the production of methanol and urea used in the UF resin production.

3.6 Ecotoxicity

As can be seen in Fig. 2, the forest production subsystem was the most important contributor to the ecotoxicity (EC) impacts, representing almost 99 % of the impacts in this category, mainly due to the use of the herbicide glyphosate in forest management activities

3.7 Human toxicity

The industrial production subsystem was the largest contributor to the human toxicity (HT) impacts (97 %), mainly as a result of free formaldehyde emissions during the MDP manufacturing process. In this category, it was checked that the impacts from UF resin were major than for all others categories.

4 Discussion of improvement opportunities

The main hotspots in the cradle-to-gate assessment of MDP in each impact category are presented in Table 5. As can be seen, the majority of the hotspots occur in the industrial production

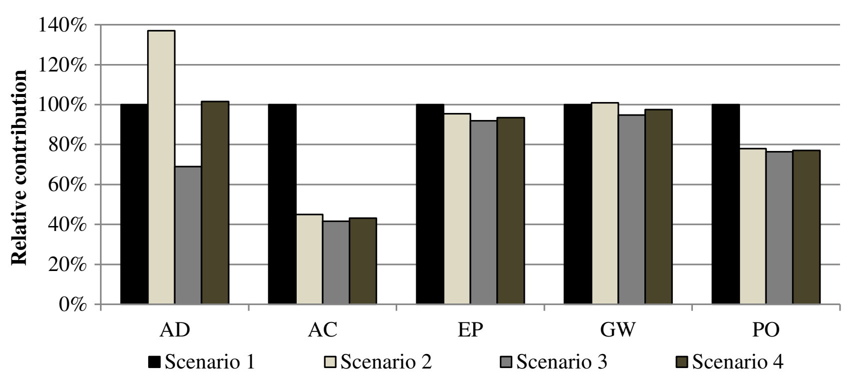

Fig. 3 Comparative environmental impact assessment of the four scenarios of heavy fuel oil substitution relative to scenario 1 (baseline)

and are mostly related to HFO and UF resin utilization. The substitution of these inputs with alternative ones with lower impacts could result in important improvements in the environmental profile of MDP. The substitution of HFO by alternative fuels (e.g., diesel or wood residues) in the MDP manufacturing process do not involve changes in the technical properties of MDP and alternative production scenarios are discussed in the following section. The substitution of UF resin for other type of resin (e.g., melamine–urea–formaldehyde, phenol–formaldehyde, isocyanate, tannin–urea–formaldehyde, etc.) could change the technical properties of the MDP and is out of the scope of this paper. On the other hand, a first approach about a LCA study of UF resin for Brazilian context was developed by Silva et al. (2013).

4.1 Substitution of heavy fuel oil by alternative fuels

Based on net calorific value, the thermal energy demand for the manufacturing of 1 m^3 of MDP (mainly for drying and pressing processes) is equivalent to 1,133 MJ and is fulfilled by the use of HFO (13.7 kg) and wood residues (38.5 kg). Four scenarios of HFO substitution were assessed:

- Scenario 1: the baseline representing the current MDP production process: HFO (13.7 kg/m^3 of MDP) and wood residues (38.5 kg/m^3 of MDP)
- Scenario 2: diesel satisfies 100 % of thermal energy requirements (equivalent to 26.4 kg of diesel per cubic meter of MDP)
- Scenario 3: wood residues satisfies 100 % of energy requirements (equivalent to 75.5 kg of residues per cubic meter of MDP)
- Scenario 4: diesel displaces HFO (equivalent to 12.9 kg of diesel per cubic meter of MDP); wood residues consumption is the same as the baseline scenario (38.5 kg/m^3 of MDP)

Figure 3 presents the comparison of the environmental profile of the four scenarios for HFO displacement. As can be seen, scenario 3 (100 % wood residues) presents the lowest impacts in all categories, although the reduction achieved compared to scenario 1 (current situation) is similar to that of scenarios 2 and 4 in AC, EP, and PO, with relative impact differences less than 2 %. Moreover, scenario 3 is the only scenario that allows the reduction of AD impacts (31 % compared to scenario 1). The major improvement potentials occur in AC. Regarding EP and GW, similar results are obtained in all scenarios. The toxicity categories (EC and HT) were not analyzed since these are not affected by HFO substitution (almost all impacts are related to other processes, as discussed in Section 3).

Scenario 3 considers that wood residues fulfill the total thermal energy demand of MDP manufacturing. Since the amount of wood residues generated per cubic meter of MDP produced (97.2 kg/m^3, see Table 2) is higher than thermal energy needs (75.5 kg/m^3), the displacement of HFO by wood residues could be implemented by MDP manufactory plants. Alternatively, if the use of a larger quantity of wood residues in Brazilian plants is not technically viable, the substitution of HFO by diesel (scenario 4) also results in an improvement similar to scenario 3, except for AD, where a slight increase in impacts compared to the baseline scenario 1 can be observed.

5 Conclusions

A cradle-to-gate assessment of MDP produced in Brazil, considering two main subsystems (forest and industrial production) was presented. Detailed inventories regarding Brazilian eucalyptus production and MDP industrial production were collected. The potential environmental impacts of MDP were assessed in terms of seven impact categories (AD, AC, EP, GW, PO, EC, and HT) in order to identify the main hotspots to assist the wood panel industry to improve their environmental sustainability. The industrial production was responsible for most of the impacts in all categories, except EC. The main hotspots identified were the use of HFO as a thermal energy source in MDP manufacture as well as the production of UF resin used as synthetic adhesive. Glyphosate herbicide was the main responsible for the impacts in EC. Scenarios for HFO substitution were assessed and results showed that substitution of HFO for wood residues was not only environmentally preferable but also viable regarding the availability of wood residues generated in-mill. The use of diesel could also constitute a viable option to reduce the environmental impacts. Further research should address UF resin production in order to improve its environmental profile as well as the possibility of using alternatives resins. Other sources of wood for MDP production could also be investigated (e.g., pine wood and wood residues) to assess potential improvements.

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